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Technical Note

CEL

TN no. N-1511

title: TUNNELING WITH CONTROLLED STRESS WAVES

author: Robert J. Odello

date: December 1977

sponsor: CHIEF OF NAVAL MATERIAL

program nos: ZF61-512-001-065

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, California 93043

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: CEL-TN-1511	2. GOVT ACCESSION NO.: DN587004	3. RECIPIENT'S CATALOG NUMBER: 9 rept.
4. TITLE (and Subtitle): 6 TUNNELING WITH CONTROLLED STRESS WAVES		5. TYPE OF REPORT & PERIOD COVERED: Final Jul 1970-Sep 1977
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): 10 Robert J. Odello		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: CIVIL ENGINEERING LABORATORY, Naval Construction Battalion Center, Port Hueneme, California 93043		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62766N; ZF61-512-001-065
11. CONTROLLING OFFICE NAME AND ADDRESS: Chief of Naval Material (Technology and Laboratories), Headquarters, Naval Material Command, Washington, DC 20360		12. REPORT DATE: 11 December 1977
		13. NUMBER OF PAGES: 18
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 12 16p.		15. SECURITY CLASS. (of this report): Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

16 F61512

18. SUPPLEMENTARY NOTES

17 ZF61512001

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Tunneling, stress waves, spalling, wave propagation, electrohydraulics.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a concept for hard rock tunneling that uses controlled stress waves to fracture rock. Tests with high explosive charges demonstrated the feasibility of the concept, but follow-on tests with an electrohydraulic stress wave source were unsuccessful. Development of a repeatable stress wave source is necessary to the success of the concept. Extrapolations of test data indicate that the concept could reduce the specific energy requirements for hard rock tunneling by an order of magnitude compared to present tunnel boring machines.

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391 111 YB

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Library Card

Civil Engineering Laboratory
TUNNELING WITH CONTROLLED STRESS WAVES (Final),
by Robert J. Odello
TN-1511 18 pp illus December 1977 Unclassified

1. Tunneling 2. Stress waves I. ZF61-512-001-065

This report describes a concept for hard rock tunneling that uses controlled stress waves to fracture rock. Tests with high explosive charges demonstrated the feasibility of the concept, but follow-on tests with an electrohydraulic stress wave source were unsuccessful. Development of a repeatable stress wave source is necessary to the success of the concept. Extrapolations of test data indicate that the concept could reduce the specific energy requirements for hard rock tunneling by an order of magnitude compared to present tunnel boring machines.

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INTRODUCTION

This report summarizes efforts begun in 1970 under the sponsorship of the Office of Naval Research (ONR) to develop a new method of tunneling in hard rock. The goal was to develop improved tunneling techniques that would contribute to the economic feasibility of hardened deep underground facilities such as communication systems or underground command, control, and communications (C^3) facilities. Most recently the Civil Engineering Laboratory (CEL) effort in this project was supported by the Director of Navy Laboratories.

Basic Concept

The concept is based on use of controlled stress waves to fracture rock as a method for tunneling in hard rock. By creating a sufficiently short compressive stress pulse in a hole drilled in the center of a cylindrical block of rock, the outer surface of the rock can be spalled when the pulse is reflected as a tensile pulse at the free face. The process is illustrated in Figure 1. Briefly, the rock face is trepanned with conventional cutters to create a free-standing horizontal core the diameter of the desired tunnel. A center hole is drilled concentric to the core, and stress pulses are created in the center hole by the electrohydraulic effect. Coring and trepanning advance as the outer surfaces of the core are spalled by successive pulses. Continuous operation produces a step-tapered core section as the tunneling machine advances.

Initial Studies and Tests

Initial studies consisted of defining the process analytically and physically and conducting tests with small explosive charges on Hydro-

stone specimens (Ref 1). The propagation of the stress wave through the rock and its reflection at the free surface were described by simple analytical methods and by a dynamic finite element numerical analysis. The results of both methods indicated that a major problem with the concept is the spatial attenuation of the stress wave as it propagates outward from the center hole. Difficulties arise when the peak pressure required at the face of the center hole exceeds the dynamic crushing strength of the rock material. The analysis also indicated that the tangential stresses that contribute to radial cracks tend to lag behind the radial stress peak; thus, desired spalls might be achieved without producing radial cracks.

Tests conducted with small chemical explosive charges in 300- and 600-mm diameter Hydrostone specimens verified the analytical results. The tests demonstrated the desirability of using water as a coupling medium between explosive and rock. By using successively smaller amounts of explosive in waterfilled holes, the desired spalls were achieved with virtually no radial cracks (Figure 2). The feasibility of achieving second and third spalls after the initial break was also demonstrated.

Results of Early Experiments

The success of the initial experimental efforts led to an attempt to spall granite specimens with an electrohydraulic stress wave source (Ref 2). The electrohydraulic equipment consisted of a power supply with a nominal output of 5 kJ per discharge for up to 3 discharges per second, a capacitor bank containing six 7.5 μF capacitors in parallel, and a power head containing the electrode gap. The controls were modified to permit single discharges at a peak voltage of 17 kV or a maximum energy of 6,500 kJ per discharge. Granite specimens were 38 cm in diameter by 46 cm high. Stress pulses were produced in a 5 cm diameter center hole 28 cm deep.

The equipment proved to be incapable of fracturing the granite in any mode. Apparently, very little of the capacitor bank energy was transmitted to the rock. Possible sources of energy loss were long cables between the capacitor bank and power head, strain energy absorbed by a waterproofing liner in the hole, and incomplete discharges.

The analytical portion of this effort led to the development of an approximate expression for determining the stress pulse characteristics necessary for circumferential spalls. The equation expresses the ratio of the peak stress on the walls of the center hole σ_o to the stress pulse duration τ in terms of rock properties and geometry. This ratio can be expressed as:

$$\frac{\sigma_o}{\tau} = f'_{td}\left(\frac{c}{2d'}\right)\left(\frac{R - d'}{r_o}\right)^n$$

where f'_{td} = dynamic tensile strength of rock

c = stress pulse propagation velocity in rock

n = stress pulse decay constant for rock

d' = thickness of the desired spall

R = outside radius of the core

r_o = radius of the center hole

Subsequent tests with the electrohydraulic pulser (Ref 3) verified several of the hypotheses regarding energy losses. Leads between the capacitors and the power head were reduced from 40 m to 0.6 m, and the polyurethane liner was removed. Hydrostone specimens were used to

obtain comparisons with previous tests using high explosives. The tests showed that the equipment was capable of fracturing Hydrostone, but the failure mode was similar to those observed in the high explosive tests when the pulse duration was too long. The results indicated that further equipment modification would be necessary.

EXPERIMENTS

The objective of the experiments described here was to reduce the stress pulse duration by decreasing the capacitance C of the electrohydraulic pulser. Reference 4 and the circuit analysis in Reference 3 indicate that shorter stress pulse durations can be produced by using less capacitance. For usual values of resistance and inductance the pulse duration is approximately proportional to $\sqrt{C}$. A possible benefit of this approach is that the energy output per pulse is directly proportional to the capacitance for a constant discharge voltage. Thus, if the specimen could be broken with the lower capacitance discharge, less energy would be required for the fragmentation process.

The tests included fracture attempts with three different levels of capacitance. All except one of the original capacitors in the CEL electrohydraulic equipment were disconnected to provide 7.5 μF, and two additional capacitors of 1.0 and 0.1 μF were purchased. These modifications permitted pulse durations of 8.7, 3.2, and 1.0, relative to the shortest duration; and maximum energy per discharge was 1,080, 145 and 14.5 J, respectively. The test setup was similar to that described for specimens 8 and 9 in Reference 4. That is, holes were drilled through the length of the specimens and linear spark gaps were used. The spark gap was 20 mm in all cases. All tests were conducted with capacitors charged to 17,000 V.

With the single 7.5 μF capacitor, the pulser broke two Hydrostone specimens in the same manner. The failure mode was the same as that obtained with high explosive charges that produced long duration pulses. Discharges using the 1.0 and 0.1 μF capacitors did not produce any cracking in the specimens, even after several shots. Discharges from the 0.1 μF capacitor were barely audible.

DISCUSSION

The experimental results were inconclusive. One is tempted to conclude that some capacitance between 1.0 and 7.5 μF could produce the desired spall pattern. However, a cross-over point between radial fractures and no fractures may occur without passing through a region in which spalling occurs. It may be possible, with the limitations of the present equipment, to encounter a region in which the stress pulse would be short enough to create spalls, but the peak pressure would not be high enough to exceed the tensile stress of the material. Reference 5 shows that for a given discharge circuit, the peak pressure varies with the voltage. Thus, since the present equipment was operated at maximum voltage, higher peak pressures could not be achieved.

It is ironic that the same factors that limited the success of these tests are the major attributes of the electrohydraulic effect. Specifically, the peak pressure and the pulse duration can be altered almost independently of each other. If the equipment has the necessary range of capabilities, any desired combination of these properties can be produced by changing the voltage and capacitance. These features would also be advantageous for tunneling-machine applications, because they would permit tailoring the stress pulse to the requirements of the rock being excavated.

Since the original goal of this effort was to investigate a concept for rock breakage that could be adapted for rapid tunneling, it would be useful to review the results from the high explosive tests for extrapolating potential performance of a tunneling machine based on these principles. Tests on a 30-cm diameter specimen of Hydrostone indicated that three shots would be required to advance the face a distance of 5 cm. If we take an extreme case and assume the energy per pulse is 10,700 J (Ref 3), the specific energy would be 9.1 J/cm^3. This value compares very favorably with specific energies of 50 to 200 J/cm^3 for present tunnel-boring machines (Ref 6). In the same manner we can extrapolate to a 4-m diameter tunnel. If we assume each spall is 1/4-m thick by 1/4-m long, seven pulses will be required to advance 1/4 m. If the energy required per pulse is scaled by the ratio of new surface area created by spalling the outermost layer, the energy per pulse would have to be 910,000 J or a total of 6,300,000 J for 1/4 m advance. The resulting specific energy would by 2.0 J/cm^3. If a similar extrapolation is made based on the specific energy required to spall the outermost layer, the energy per pulse would be 3,800,000 J, and the specific energy would be 8.5 J/cm^3. Both of these values represent significant energy savings over tunnel-boring machines. If the electrohydraulic equipment were powered by a 500 kW source, it could supply one pulse every 7.6 seconds. This would produce a maximum advance rate of 28 cm/min.

Constructing a full-scale prototype to meet these requirements would not be easy. Peak pressures on the order of 1,600,000 kPa would be required to spall hard rocks like granite. Pressures of this magnitude would probably produce localized crushing around the center hole. Pulse durations would have to be on the order of 60 μs or less. In order to satisfy these requirements the voltage on the capacitors would have to be on the order of 300 kV. High voltage equipment of this magnitude may be difficult to design for the typical tunnel environment.

The interpolation from the 300-mm specimens to a 4-m diameter tunnel was based on "worst case" test data. The calculations indicate, however, that the concept is marginally feasible. If the "best case" data are used the resulting prototype characteristics would be as follows:

Energy per pulse	800,000 J
Specific energy	1.8 J/cm^3
Maximum advance rate (500 kV power source)	130 cm/min
Maximum voltage	130 kV

Although these reults are overly optimistic, they demonstrate the great potential of the proposed tunneling concept. If these characteristics can be achieved, they would represent an order of magnitude improvement in hard rock tunneling technology.

ALTERNATIVE CONCEPTS

The use of controlled stress waves to excavate hard rock is such a promising concept that other stress wave sources should be considered in case electrohydraulics prove to be impractical.

A reasonable first approach would be to investigate concepts that use chemical explosives in a controlled, continuous process. Using the same extrapolation procedures as for the electrohydraulic concept, the amount of explosive required per pulse would be between 160 and 770 grams of TNT equivalent. One method of creating the stress pulse would be to pump a diluted liquid explosive into the center hole and detonate it with a relatively low energy spark discharge. A primary difficulty with this approach is the safety aspects of such an explosive in a tunnel. Handling safety could be achieved by using a two-component system (each component of which is not sensitive until mixed). Problems

of fumes and containment would be difficult to overcome unless remote-control methods could be used to keep personnel away from the face of the tunnel. The design of hardware that could absorb such blasts on a continuing basis would also be difficult.

Another approach to consider is that of other configurations in which the stress pulse would not attenuate as rapidly as in the cylindrical diverging configuration. An ideal configuration would be use of a converging cylindrical stress wave with the present configuration; however, the problem of creating such a stress wave in the outer kerfs seems formidable. Rectangular and triangular kerfs have also been considered, but the problem of creating high magnitude stress pulses over large areas still exists.

The spiral blasting technique is a concept proposed by others that also uses stress waves and tensile fractures to advantage (Ref 7). In this concept blast holes are drilled along radial spokes so that the holes for each succeeding spoke are deeper. The process is started with a plane free face along a drill line. The adjacent row of spokes is loaded and blasted so a wedge is spalled. Succeeding rows of drill holes spall succeeding wedges, and the tunnel advances along a spiraling face. The basic concept is not new, but its mechanization is relatively recent. A presently proposed method uses small explosive charges to spall the wedges as protected drills are creating the next series of blast holes. Electrohydraulics might be easily adapted to this method because the energy and voltage requirements would not be excessive. Electrohydraulics could help increase the advance rate because it would require less delay time between shots.

SUMMARY AND RECOMMENDATIONS

This report has traced the history of the development of a concept for hard rock tunneling which uses controlled stress waves rather than full face cutters to remove rock. Initial successes with small explosive

charges led to a series of experiments with electrohydraulic stress wave sources in order to develop a continuous tunneling process. Although the electrohydraulic equipment available could not produce the desired fracture pattern, data from these experiments and from the high explosive tests were extrapolated to a full-scale tunnel. The extrapolation indicated that the concept may or may not be feasible, depending on the assumptions. Alternative stress wave sources and tunneling geometries were discussed.

This study to date has been supported by funding which was earmarked for high-risk/high-payoff investigations. Unfortunately, the results have shown that the basic concept is still in that category. The major roadblock is the development of a stress wave source. The most promising source appears to be electrohydraulics, but more basic research is needed to permit full understanding and control of the stress wave characteristics. Chemical high explosives might also be used as stress wave sources. Therefore, future studies of the proposed tunneling technique should be devoted to synthesizing and characterizing a suitable stress wave source.

ACKNOWLEDGMENTS

Many people have contributed to this effort as sponsors, advisors, and investigators. Mr. J. R. Allgood, formerly of CEL, conceived the basic concept. Sponsor representatives included Dr. T. P. Quinn and J. L. Warner of ONR; Dr. B. Kruger and E. Pray of the Naval Electronic Systems Command; J. R. Williams and Dr. K. Goering of DNA; and W. F. Burkart of CEL. Fellow CEL staff members who made significant contributions were R. N. Murtha, T. K. Lew, T. A. Shugar, D. T. Corrente, V. J. Gerwe, and L. D. Underbakke.

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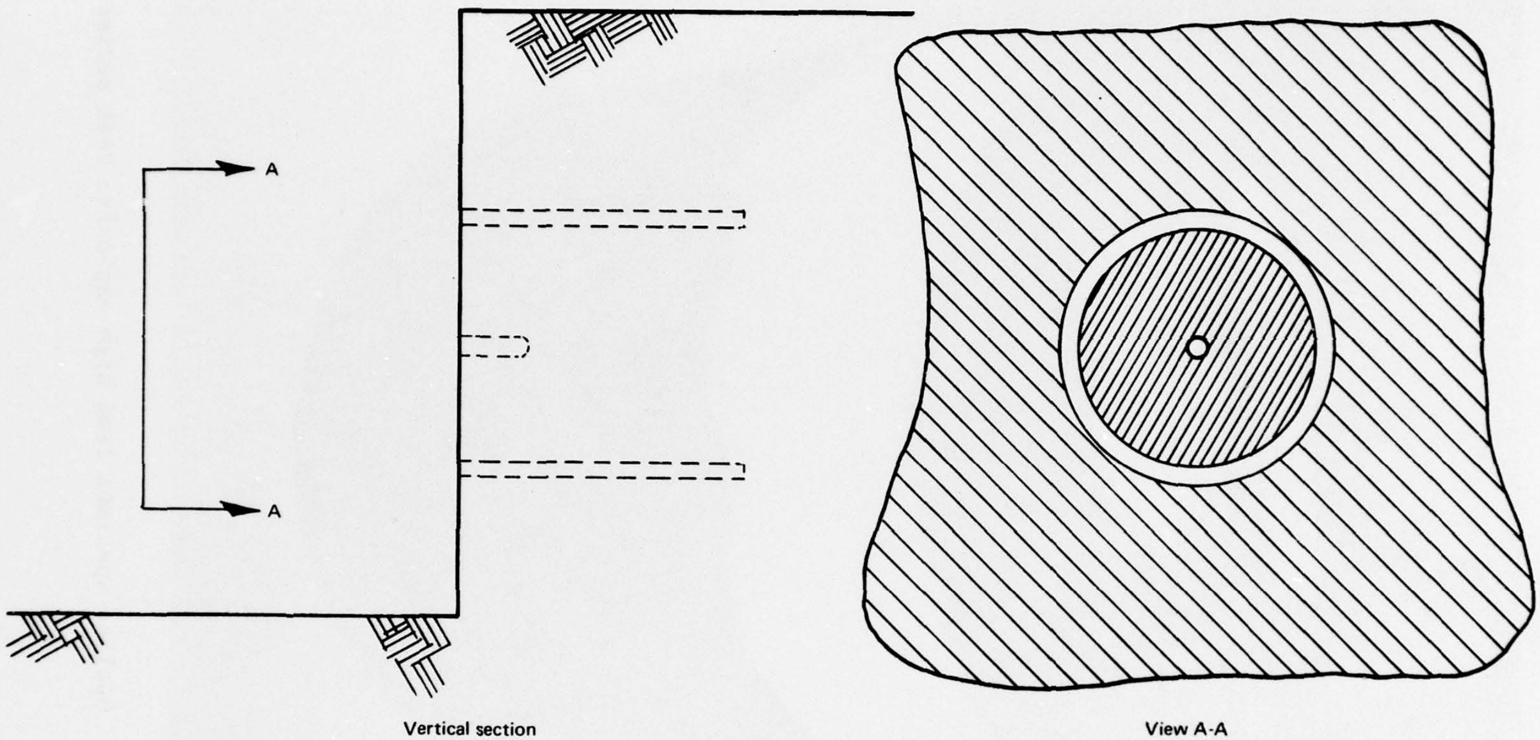

Figure 1. Trepanned rock core.

Figure 2. Spalled specimen from high explosive test series.

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NAVSHIPYD CO Marine Barracks, Norfolk, Portsmouth VA; Code 202.4, Long Beach CA; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 380, (Woodroff) Norfolk, Portsmouth, VA; Code 400, Puget Sound; Code 404 (LT J. Riccio), Norfolk, Portsmouth VA; Code 410, Mare Is., Vallejo CA; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; Code 440.4, Charleston SC; Code 450, Charleston SC; L.D. Vivian; Library, Portsmouth NH; PWD (Code 400), Philadelphia PA; PWD (LT N.B. Hall), Long Beach CA; PWO, Mare Is.; PWO, Puget Sound; SCE, Pearl Harbor HI; Tech Library, Vallejo, CA
NAVSTA CO Naval Station, Mayport FL; CO Roosevelt Roads P.R. Puerto Rico; Engr. Dir., Rota Spain; Maint. Cont. Div., Guantanamo Bay Cuba; Maint. Div. Dir/Code 531, Rodman Canal Zone; PWD (LTJG P.M. Motodlenich), Puerto Rico; PWD/Engr. Div, Puerto Rico; PWO Midway Island; PWO, Guantanamo Bay Cuba; PWO, Keflavik Iceland; PWO, Mayport FL; PWO, Puerto Rico; ROICC Rota Spain; ROICC, Rota Spain; SCE, Guam; SCE, San Diego CA; SCE, Subic Bay, R.P.; Utilities Engr Off. (LTJG A.S. Ritchie), Rota Spain
NAVSTA BISHOPS POINT Harbor Clear. Unit one, Pearl Harbor, HI
NAVSUBASE LTJG D.W. Peck, Groton, CT
NAVSUPPACT CO, Brooklyn NY; CO, Seattle WA; Code 4, 12 Marine Corps Dist, Treasure Is., San Francisco CA; Code 413, Seattle WA; LTJG McGarrah, Vallejo CA; Plan/Engr Div., Naples Italy
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NAVTECHTRACEN SCE, Pensacola FL
NAVWPNCEN Code 2636 (W. Bonner), China Lake CA; PWO (Code 26), China Lake CA; ROICC (Code 702), China Lake CA
NAVWPNSTA (Clebak) Colts Neck, NJ; Code 092, Colts Neck NJ; ENS G.A. Lowry, Fallbrook CA; Maint. Control Dir., Yorktown VA; PW Office (Code 09C1) Yorktown, VA
NAVWPNSUPPCEN Code 09 (Boennighausen) Crane IN
NAVXDIVINGU LT A.M. Parisi, Panama City FL
NCBU 405 OIC, San Diego, CA
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NCBU 411 OIC, Norfolk VA
NCR 20, Commander
NCSO BAHRAIN Security Offr, Bahrain
NMCB 133 (ENS T.W. Nielsen); 5, Operations Dept.; 74, CO; Forty, CO; THREE, Operations Off.
NORDA Code 440 (Ocean Rsch, Off) Bay St. Louis, MS
NRL Code 8400 (J. Walsh), Washington DC; Code 8441 (R.A. Skop), Washington DC; Rosenthal, Code 8440, Wash. DC
NSC Code 54.1 (Wynne), Norfolk VA

NSD SCE, Subic Bay, R.P.
NTC Code 54 (ENS P. G. Jackel), Orlando FL; Commander Orlando, FL; OICC, CBU-401, Great Lakes IL; SCE Great Lakes, IL
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